OPTIMIZATION OF THE NOMINAL CYCLE

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Abstract

The energy ramp and the betatron squeeze are critical phases of the LHC operation. During the squeeze, delicate optics manipulations take place when the stored energy is maximum. In 2010, ramp and squeeze were commissioned rapidly and smoothly became operational. On the other hand, during the first commissioning exercise, the focus was put on machine safety and on operational robustness rather then in efficiency for luminosity production. After having accumulated a full year of experience on the operational cycle and having gained important feedback on machine behaviour and operational procedures, it is now time to address the optimization of the LHC cycle, while still respecting safe boundaries. In this paper, the experience with the LHC operational cycle is reviewed, possible bottlenecks are identified and paths for improvements are addressed. Proposals for improvement are based on a critical look at the limiting factors encountered in the different phases of the cycle. More complex operation configurations, like combined ramp and squeeze, are also discussed.

INTRODUCTION

The optimization of the machine cycle will be a crucial parameter for the LHC performance during stable running conditions in 2011 at a luminosity above $10^{32}\text{cm}^{-2}\text{s}^{-1}$. Minimizing the turnaround time will have a direct impact on the integrated luminosity. While in the first commissioning year the focus was rather put on bringing up safely the peak luminosity performance in preparation for the 2011 run, it is now important to address optimization issues in view of maximizing the LHC physics reach. Clearly, machine safety remains the priority and the optimization process must be carried out within well-defined safety boundaries.

At the LHC, energy ramp and betatron squeeze are carried out with functions of well-defined time length. An optimization of the duration of these functions has a direct impact on the machine turn around. On the other hand, other important phases of the operational cycle (injection, flat-top setup, preparation of collisions, ...) are also important. The duration of these phases depends on a large number of aspects, such as operational efficiency, status of procedures, availability of automated sequencer tasks, etc. There is often much margin for improvement there. An optimization of the machine cycle must hence take into account the various aspects of the whole operational phases while ensuring a reasonable machine flexibility. Indeed, the results presented here are based on a statistical analysis of the time spent in the various phases, as presented in [1] with the aim to find the real bottlenecks.

In 2010, ramp and squeeze settings have been prepared taking conservative assumptions and the hardware and beam parameters. For example, all the available matched optics where used and stepped through while squeeze, with a subsequent lengthening of the squeeze duration (every new optics adds some extra time due to the constraints on the power converter settings). This approach ensured minimum errors of key beam parameters and full flexibility in the commissioning, at the expenses of longer collision setup time during physics fills. These aspects will be reviewed in preparation for the 2011 run.

After a brief recap. of the different phases of the LHC operational cycle, the outcome of previous studies on turnaround optimization [1] are recalled. For each operational phase, possible improvements are outlines. The feasibility of combining ramp and squeeze is also discussed, with an outline of pro's and con's and with a proposal for the actions in 2011. Finally some conclusions are drawn.

LHC OPERATIONAL CYCLE IN 2010

The main phases of the LHC cycle are illustrated in Fig. 1, where beam intensities (top) and magnet currents (bottom) are given as a function of time. The current of a main dipole circuit and of a matching quadrupole circuit (Q5-L1B1) indicate the times when ramp and squeeze take place. In the cycle, four phases involve execution of time functions of well-defined time length:

- *energy ramp*: 1400 s for are required to ramp from 450 GeV to 3.5 TeV, at a maximum dipole ramp rate of 10 A/s, including a 380 s flat-top *plateau* for field decay compensation;
- *betatron squeeze*: 1041 s for the change to β^*=3.5 m at 3.5 TeV in all IPs (initially commissioned to β^*=2.0 m in 1285 s;
- *collision functions* to collapse the parallel separation bump: 108 s for protons, 180 s for ions that also required a change of crossing angle;
- *magnetic pre-cycle* without beam: 2100 s if started from top-energy, 3100 s if started from injection.

While time-functions are being executed for the main accelerator systems (power converters, collimators, RF), the

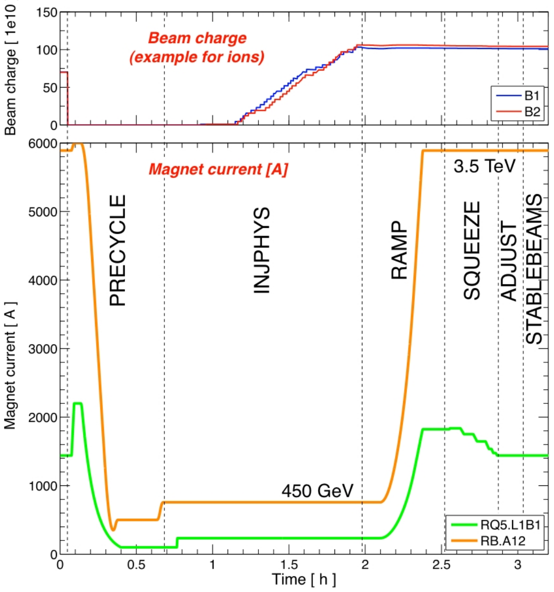

Figure 1: LHC operational cycle with the main phases, illustrated by graphs of beam intensity (top) and magnet currents (bottom) as a function of time. The current of a matching quadrupole is used to show when the squeeze takes place.

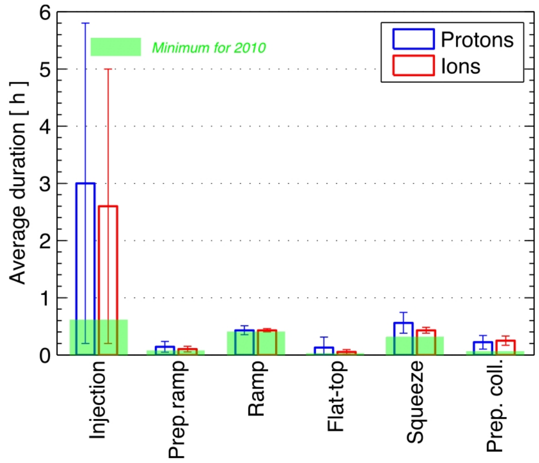

Figure 2: Distribution of average times spent in the different operational phases, calculated over about 30 physics fills at the end of the 2010 run. The theoretical minimum durations calculated for the 2010 parameters are indicated by the green bars [1].

machine is essentially "frozen" and no trims of any parameter are possible. Feedback systems for tune and orbit use dedicated real-time channels that are added on top of the operational settings being executed by the hardware.

Other operational phases that do not have a well-defined duration, are

- *injection* of probe beams for machine setup and physics beams for filling;
- *ramp preparation*;
- *flat-top adjustments*;
- *adjust* at the end of the squeeze to prepare collisions;
- *stable beams* for physics data taking.

In these phases, the machine sits at constant "actual" settings that can be changed as discrete trims, not synchronized across the systems, depending on the operational needs (optimization of injection oscillations, orbit steering, changes of tune and chromaticity, etc.). The duration of these phases depends of various aspects and the details of the operational procedures. During 2010, the mode of operation kept evolving from a paper-based procedure towards fully sequencer-driven operation (less room for mistakes, faster execution of tasks, better reproducibility of machine configurations).

The optimization of the duration of ramp and squeeze is important because on paper these phases are the ones that take the longest times. On the other hand, in practise it is important to maintain a good overview of the time spent in all the phases in order to achieve an optimized strategy: it does not pay off to propose aggressive buts in the squeeze time until the machine is being limited but other bottlenecks. A reduced operational flexibility must always be justified by a real gain. The overview of the bottlenecks for turnaround performance is based on the statistic analysis of the physics fills on 2010.

2010 TURNAROUND EXPERIENCE

This section summarizes the results presented in [1] that are based on the statistical treatment of approximately 30 successful physics fills achieved with a stable machine configuration at the end of the 2010 run. The period that saw the performance ramp up to $2 \times 10^{32}\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with total stored beam energies up to about 30 MJ, is considered. To a large extend, the mode of operation at the end of 2010 is closest to what has to be expected for the 2011 run (well-established procedures, high level of automation through appropriate software, minimum change of machine configuration during standard operation). The last month dedicated to ion operation has also been considered in the study.

The time spent in the various operational phases in the running period considered as a reference, are given in Figs. 2 and 3 (the latter is a zoomed out version of the former to show details of the phases that took in average less than 1 hour). As pointed out in [1], the theoretical minimum durations for the 2010 parameters are actually longer than the nominal values as of LHC design report [2]. For example, the injection times in 2010 were much longer than foreseen initially because we could not achieve dedicated filling of the LHC, due to time required for the quality checks.

The minimum LHC turnaround time from beam dump to next stable beams was about 2h45 for the case with

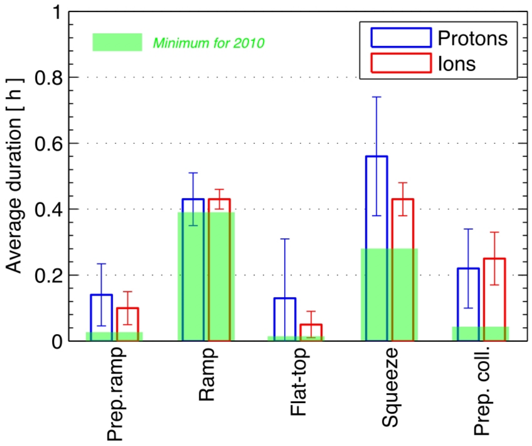

Figure 3: Zoomed version of Fig. 2 for the operational phases that took in average less than 1 hours.

dipole ramp rate of 10 A/s and 3h40 for 2 A/s. The average turnaround time for the successful physics fills considered above, without taking into account faults that stopped the beam operation [3], was well about 4h30 (sum of the blue bars of Fig. 2). The pre-cycle time has to be added to this duration, for a total time of about 5h30. A detailed analysis of the time spent in the various operational phases shows that:

- The turnaround efficiency is by far dominated by the filling time. This includes machine setup with probe beam and filling of physics beams (bunch trains).
- The squeeze took in average twice its minimum time. This is mainly caused by the manual actions required to prepare the squeeze and by the fact that in 2010 we stopped at intermediate points to change references of tune and orbit feedbacks and to move collimators. This mode of operation has also the draw-back that collimator settings are not optimized for triplet protection (evolution of local beam size not followed smoothly).
- Stopping points in the squeeze, involving delicate beam manipulations and setting changes for the feedbacks, were a primary source of operational mistakes that causes time consuming beam dumps at top-energy.
- The ramp itself took in average the expected time (functions were executed without interruptions). The preparation for ramp can certainly be improved as it took in average 30 minutes.
- In general, all the phases that required manual interventions took significantly longer than foreseen.
- With long turnaround times, operational mistakes are are time consuming and should be minimized through well-established procedures and sequences. Optimized strategy should not jeopardize a robust operation.

The considerations above are used as a guideline to identify areas of improvement for the overall machine cycle. In general, it appears clear that in 2010 the operational cycle duration was not yet limited by the intrinsic duration of the functions for ramp and squeeze but rather from the injection process and from the manual interventions associated to the beam setup, preparation of functions, beam measurements, etc. This must be taken into proper account while proposing "aggressive" strategies for ramp and squeeze.

It is however important to stress that the turnaround performance in the first year of operation was certainly remarkable for a machine of the complexity of the LHC. It is nevertheless legitimate to have a critical look at the experience accumulated in order to identify paths for improvements.

IMPROVEMENTS FOR 2011

Pre-cycle

Issues related to the pre-cycle are discussed in detail in [3, 4] and are not reviewed here. It is just reminded that at the end of the operation in 2010 we achieved an efficient machine setup without beam: all the preparatory task for re-establishing injection after a beam dump (or a powering failure requiring a pre-cycle) can be done in the shade of the pre-cycle. Operationally, it is therefore difficult to optimize further the setup time without beam unless the magnet hardware parameters are changed to allow a faster pre-cycle.

It is also worth mentioning that a dedicated access procedure has been established [5] to allow access in the machine while keeping the main dipole magnets at the stand-by current of 100 A/s and the rest of magnets at injection currents. A reduction of the minimum dipole current during pre-cycle has been foreseen accordingly to avoid a full pre-cycle after a short access [3]: in some specific cases, the dipoles can be kept at 100 A/s while people are in the machine and then ramped directly to their injection currents. The impact on dynamic effects of the magnets will require a dedicated validation by beam measurements [6].

Injection and ramp preparation

Aspects related to possible reduction of the duration of the filling time have been addressed in various companion papers at this workshop [7, 8] and at the Evian2010 workshop [1, 9, 10, 11]. A few proposal that came out as strong operational requests are listed here:

(1) Injection losses caused by halo tails or by un-captured beam in the LHC [7, 8]. This issue was inducing loss of time also due to tight loss thresholds in the injection quality checks, which often caused injection interlock without serious issues for the machine (operational tolerances were too tight and the operation crew was instructed to simply ignore them).

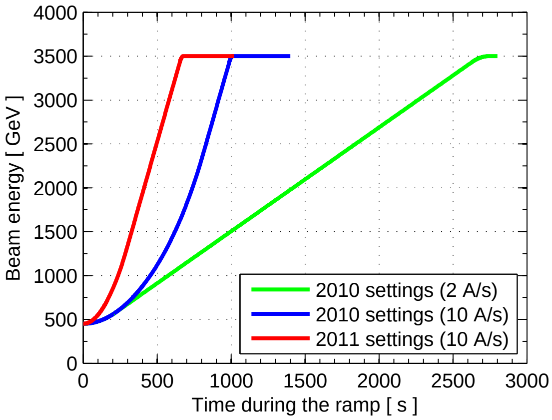

Figure 4: Different ramp settings for the main dipoles used in 2010 and foreseen for 2011. Courtesy of M. Lamont.

(2) Interleaved injection requests must be possible. In 2010, the injection request of one beam was only possible after injection and quality checks of the other beam were completed. In case of problems or analysis delays, the other beam would be stopped for up to a few SPS cycles of more than 40 s. This was a recurrent problem that caused significant losses of time.

(3) Injection times were often increased due to the long preparation times for the LHC beams in the injectors. The LHC beam preparation is very demanding for all the injector chain and hence the beam preparation must start early on in order to be ready for the LHC injection.

(4) The LHC setup at injection was also often long. Preventive trims of tune and chromaticity are under preparation by FiDeL and LSA teams to speed-up the setup of probe beams prior to the high-intensity injection. This will minimize the dependence on dynamic effects at injection.

These issues and being addressed together with other proposals to improve the injection process [7].

Ramp and flat-top

Once the preparation for the energy ramp was completed, rarely problems were experiences with the energy ramp. Possible improvements are still possible:

(1) Faster ramp functions have been prepared to reduce the intrinsic duration of the energy ramp. This is shown in Fig. 4, where ramp settings used in 2010 and a proposal for the 2011 operation are given. The proposed change does not rely on modifications of the hardware parameters but on an improved algorithm for the parabolic-exponential branch at the start of acceleration.

(2) The decay *plateau* at flat-top will be reviewed after having gained experience with the new ramp settings. For the time being, 380 s are used to compensate decay of orbit, tune and chromaticity.

(3) In 2010, the parallel separation in all IPs was kept constant at the injection value of $\pm$ 2 mm and was reduced only after the squeeze in order to bring the beams in collision. In 2011, it will be reduced during the energy ramp with the beneficial effects of (1) improving the top-energy aperture in view of the squeeze and (2) reducing the time required to steer the beams in collision. Also the the crossing angles will be changed during the ramp to their final values for collision. This will simplify considerably the operation of the orbit feedbacks at top energy (operator manipulations have been often the source of errors).

It is important to not that a pre-requisite for item (3) is that the orbit feedback must be updated to allow dynamics changes of reference. This new implementation is foreseen [12] and will be addressed by beam tests as soon as possible at the beginning of the 2011 operation.

It is also noted that in 2011 focus will be put in establishing one single orbit reference throughout the operational cycle, to simplify the handling of reference and to reduce to a minimum the changes of feedback configurations.

After the ramp, the preparation for the squeeze required a certain number of manual actions (change of orbit references, preparation of tune feedback configuration to allow the change of tune at the beginning of the squeeze, switching off transverse damper, etc.) that will be automatized/improved in 2011.

Squeeze

As shown in Fig. 3, on average the squeeze in 2010 took a factor two longer than its minimum time given by the length of the functions for power converters and collimators (1041 s to achieve 3.5 m in all IPs). This figure improved by more than 20 % during the ion operation, thanks to better established procedures and automated sequences, but still is well above the minimum achievable. The main source of delay in the squeeze was caused by the fact that we stopped in 2 points to (1) updated orbit feedback reference with different crossing angle values and to (2) move the tertiary collimators at $\beta^* = 7$ m in all IPs with a discrete step to bring them at their final protection settings. In addition to the time lost, these manual interventions where often the source of operational mistakes that caused beam dumps.

One of the main aims for the commissioning in 2011 is to operate the squeeze in one single step from injection optics to the final β^* values. This will be possible if (1) feedbacks will allow execution of time-dependent reference, as already required for the change of orbit reference during the ramp, and if (2) the tertiary collimators in the IRs will be moved as well with functions of time to follow the evolutions of the local beta functions (collimator settings are expressed in units of local beam sizes, which change while

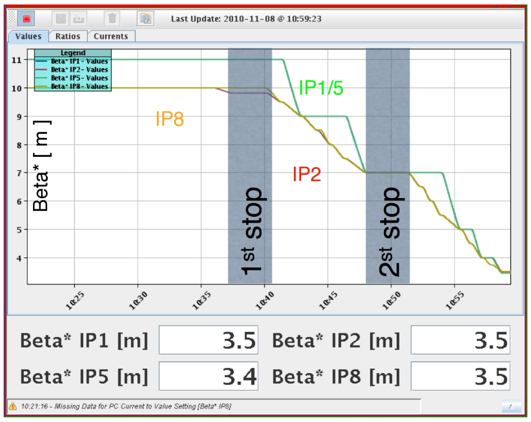

Figure 5: Example of β^* versus time in all IPs during the betatron squeeze. The two stopping points are indicated by the gray rectangles.

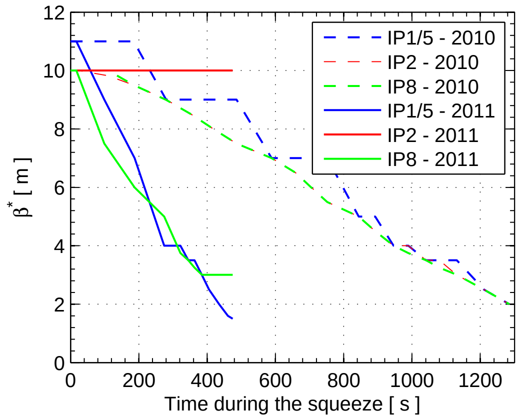

Figure 6: Beta functions in all IPs as a function of time during the squeeze in 2010 (dashed lines) and in 2011 (solid lines). The 2011 proposal must be validated during the beam commissioning. Details in [16].

the optics is modified). Moving collimators with functions is possible and was already achieved in 2010 [13, 14] but is only possible if there are no stop points. Due to the present implementation of the handling of critical settings [15], collimator limit functions can only be run through continuously. This was not possible last year due to the stop point for updating the orbit feedback reference.

In addition to removing intermediate stop points, the length of the squeeze functions has been significantly reduced by optimizing the number of matched points [16]. Simulations have shown that a number of matched points at $\beta^* > 5$ m can be safely removed while maintaining under control tune, chromaticity and orbit errors. In addition, a bug in the generation was found which caused setting functions about 30 % longer than necessary. The new squeeze functions for the 2011 baseline values [17] of $\beta^*_{\mathrm{IP1/5}} = 1.5$ m and $\beta^*_{\mathrm{IP8}} = 3.0$ m are 475 s long, as shown in Fig. 6. Details of the calculations that allowed this reduction are given in [16].

Note that removing matched points, not only increase the maximum deviations from the nominal optics, but also prevents the possibility to stop the function execution (by construction, only at matched points the conditions of zero rate and acceleration for power converters are met). The squeeze length optimization has therefore been done by removing only points already tested in 2010: all the available optics below 3.5 m have been used.

Preparation of collisions

In 2010, the time required to bring the beams in collisions was limited by the ramp rate of the IP orbit correctors RCBX that are used to collapse the separation bumps and change the crossing angles. This time will be reduced in 2011 by a factor 2-3 for a total of less than 60 s instead than 108 s (protons) and 180 s (ions). While the hardware parameters will remain the same, the reduction in time is achieved by reducing the IP beam separation already during the ramp, from ± 2.0 mm to ± 0.7 mm. Dynamic orbit reference for the feedback will also allow to reach during the ramp the collision values for the crossing angles.

COMBINING RAMP AND SQUEEZE

From the 2010 operational experience, it is seen that the machine cycle can be significantly optimized without necessarily reducing the length of the ramp and squeeze functions (even though there is indeed the plan to gain something there as well). To other options are in principle possible to optimize further the machine cycle:

(1) drive the machine through continuous settings functions for ramp, squeeze and collision;

(2) perform part of the squeeze already during the ramp.

These options have two main advantages: (i) they would reduce the duration of the nominal cycle; (ii) they would virtually reduce to zero the risk of human mistakes associated to the manipulations presently required in the different preparatory phases. Both options are in principle possible. The machine reproducibility is excellent and there are no indications that problems could occur, as it is proved by the fact that rarely in 2010 manual trims were required after the injection setup. The present architecture of the LHC controls software allows to achieve both options with some software development: (1) would required minor modifications and a more optimized mechanism to handle stop points; (2) required a new implementation to handle properly ramp and squeeze generation that presently are handled separately.

On the other hand, both methods have also possible draw-backs: (i) the potential gain in time might be jeopardized by the fact that more test ramps with pilot intensities will be needed during the year for setup, as in standard operation with high intensities it will never be possible to optimize the machine (tune, orbit, chromaticity, ...) until the end of the squeeze; (ii) the operational flexibility will be reduced in various ways; for example, it will not be possible to stop at flat-top or at intermediate β^* steps during the ramp; (iii) for option (2), the critical squeeze steps can only be performed at top energy due to aperture limitations; the most time-consuming steps will remain to be done at top energy; (iv) all together, if the new proposal of cycle optimization are implemented, the new operational cycle will be shorter than in 2010.

Taking into account pro's and con's, it has been agreed that the two options will not be pursued in preparation for the 2011 operation. Focus will be put in achieving the improvements an the other fronts, as outlined in the previous section. The options described here remain interesting for the future and will be addressed in dedicated MD studies.

CONCLUSIONS

The performance of the LHC in 2010 has been excellent in various respects. The machine cycle and the turnaround times have reached a maturity which has rarely been achieved in such a short time in accelerator of a complexity comparable to the LHC. The experience gained in the first commissioning year, has nevertheless enlightened possible ways to improve significantly the machine turnaround time. Possible paths for an optimization of the LHC operational cycle have been identified and are being addressed in preparation for the 2011 re-commissioning. There is a very concrete hope that in 2011 the cycle will be significantly shorter (probably 1 h less than in 2010, without taking into account the time for filling), less human error prone, more stable and easier to operate (less changes of reference, more and more automated through sequences). A critical item that must be addressed with high priority is the duration of physics fill injection. These results will be obtained thanks to a close collaboration between the operation and controls teams, in collaboration with the system teams.

The potential gains that are already on the table, and the clear need for commissioning flexibility, have for the moment lessened the appeal of more aggressive paths for cycle improvements, like combined ramp and squeeze in various forms. These studies remain attractive as future options and will be pursued as MD studies in 2011. In 2011, also aspects related to the dynamic squeeze with colliding beams will be addressed as a possible option for luminosity levelling.

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